AN INQUIRY INTO THE NATURE OF ELECTRICAL DISCHARGES IN AIR AND GASES.

By John Trowbridge.

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In a previous communication * I have described with some detail the installation of a storage battery of ten thousand cells, and I gave a preliminary account of some of the effects produced by this battery. It seemed desirable to utilize to the utmost its ability to produce high electromotive force. Hitherto investigators have been limited to a comparatively narrow range of inquiry on this subject; and this paper therefore contains an account of an incursion into what may be termed a new region, in which matter is subjected to an unusual electrical stress.

The discharge from a large number of Planté cells is characterized by a sibillant flame, which, by quickly separating the spark terminals, can be drawn out to a length of several feet. It closely resembles the light produced by passing an electric spark through lycopodium powder. When a photograph of this flaming discharge is examined, it is seen to have an intensely bright spark as a nucleus. On account of the flaming discharge it is difficult to examine its character by means of a revolving mirror. By employing, however, two spark gaps, it seemed possible to ascertain whether the discharge is oscillatory or not.

In my experiments the circuit was made at the instant the revolving mirror was in the position to reflect an image of the discharge of the battery upon a sensitive plate. The photographs obtained in this way showed disruptive discharges superimposed upon a continuous discharge. The latter, however, masked any appearance of an oscillatory discharge. It was evidently necessary to blow out the flaming discharge in order to see if oscillations followed the pilot discharge. The first experiment was made with 2500 cells arranged in series; and the flaming discharge was much lessened both by the reduction in the number of cells and by a suitable arrangement for blowing it out. On developing the photographs

* These Proceedings, XXXII. 253.

it was found that the discharge was an oscillatory one; for as many as five or six clearly defined oscillations followed the first, or pilot discharge. The number of cells was then doubled; and, although more difficulty was experienced with the flaming discharge, oscillations were again obtained.

On the supposition that each cell of the battery can be regarded as a leaking condenser, and that it is equivalent in capacity to a condenser shunted by a resistance equal to that of the electrolyte, we can treat such a cell as a conducting condenser under the influence, during discharge, of a periodic current. The analysis of this well known case is as follows.*

Let $A\,B\,C$ and $A\,E\,C$ be two circuits, the circuit $A\,B\,C$ being a shunt to the circuit $A\,E\,C$, which contains a condenser E.

Let L be the coefficient of self-induction of $A\,B\,C$, R its resistance, C the capacity of the condenser in the circuit $A\,E\,C$, and r the resistance of the wires leading to the plates of the condenser.

Then, if i is the current through $A\,B\,C$, and x the charge on the plate nearest to A,

$$L\frac{d\,i}{d\,t} + R\,i = r\,\frac{d\,x}{d\,t} + \frac{x}{c}.$$

Since each of the quantities is equal to the electromotive force between A and C.

If $i = \cos \rho\, t$,

$$\text{then } x = \frac{(L^2\rho^2 + R^2)^{\frac{1}{2}}}{\left(\frac{1}{C^2} + r^2\rho^2\right)^{\frac{1}{2}}} \sin(\rho\, t + a),$$

$$\text{where } a = \tan^{-1}\frac{L\,\rho}{R} + \tan^{-1}\frac{1}{r\,\rho\,C}.$$

$$\text{Hence } \frac{d\,x}{d\,t} = \frac{\sqrt{L^2\rho^2 + R^2}}{\frac{1}{C^2\rho^2} + r^2}\cos(\rho\, t + a).$$

Thus the maximum current along $A\,E\,C$ is to that along $A\,B\,C$ as

$$\sqrt{L^2\rho^2 + R^2} \text{ is to } \sqrt{\frac{1}{C^2\rho^2} + r^2}.$$

Or if we neglect the resistance r of the leading wires, as

$$\sqrt{L^2\rho^2 + R^2} : \frac{1}{C\,\rho}, \text{ or, neglecting } L, \text{ as, } \frac{R}{\frac{1}{C\,\rho}}.$$

* See Elements of Electricity and Magnetism, by Prof. J. J. Thomson, p. 431.

In the case of one cell of the battery the polarization capacity is undoubtedly very large. C. M. Gordon * finds that the polarization capacity of two surfaces of platinum 0.65 $cm.^2$ separated by an interval of 2 mm. amounts to more than 50 microfarads. The cells of my battery consist of lead plates of about 10 $cm.^2$ surface separated by about 6 mm. The layer of peroxide of lead undoubtedly gives a large polarization capacity. The resistance of each cell is about one quarter of an ohm. Even with this small value of R, oscillating currents such as my experiments show arise when the battery discharges through air or gases. A large portion of the oscillating currents pass through the condenser circuit, and the electrolyte acts as a semi-insulator. With a very high value of p, no current would pass through the electrolyte, and the cells would therefore act like Leyden jars. In the case I am considering, the Planté cells evidently act like leaky Leyden jars coupled in series. If C is the apparent capacity of one cell, $\frac{C}{n}$ would be the capacity of n cells.

An examination of the photographs of the oscillations produced by 2,500 cells, showed an apparent capacity of about 1,000 electrostatic units. Five thousand cells gave an apparent capacity of about 500 electrostatic units, as should be the case. The small apparent capacity C results from the leaking of the condenser due to the conduction through the electrolyte.

Since the discharge from an accumulator of a large number of cells is, in general, oscillatory, I am led to the belief that the discharge from any primary battery is also oscillatory, for in all cases we have to deal with capacity and self-induction. It is evident that a galvanometer in circuit with a Geisler tube or a telephone cannot detect the oscillatory discharge, since it is of high period. Moreover, when a Geisler tube is lighted by a large battery with no resistance save that of the Geisler tube and the battery in the circuit, and the light is examined in a revolving mirror by the eye, no oscillations or intermittence of light can be perceived on account of the flaming discharge through the rarefied gas.

The oscillatory discharge may be said to be the common occurrence of nature in the case of electrical discharges, and the one direction discharge the uncommon. This has been expressed by the remark that electricity takes the path of least resistance; this common belief, however, must be modified under certain conditions of resonance. In general, nature avoids a unidirectional discharge.

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* Wied. Ann., No. 5, 1897, p. 28.

A large storage battery exhibits in an interesting manner the time necessary to change condensers to a definite potential. When the inner coating of a Leyden jar of about 10,000 electrostatic units is connected with one pole of the battery, and the other rests upon a wooden table upon which the Leyden jar is placed, this jar will discharge through a small spark gap once in about ten seconds. When this latter terminal is connected directly with the outer coating of the jar, the rapidity of discharge increases to at least one hundred a second, and appears to the eye to be continuous. The battery acts like a reservoir, and continually supplies the loss in the jar. I was interested to ascertain whether the capacity in the circuit influenced the breaking down effect in air and in oil. Without external capacity boiled linseed oil broke down between small spheres — at a distance of one millimeter — under a difference of potential of 20,000 volts. A sheet of microscopic cover glass $\frac{1}{250}$ of an inch in thickness was not, however, perforated, and a sheet of mica $\frac{1}{1000}$ of an inch in thickness also withstood this difference of potential. When a capacity of 10,000 electrostatic units was employed no difference could be observed in the breaking down effect. When therefore a powerful storage battery is employed to generate a difference of potential, it apparently serves the purpose of maintaining a full difference of potential between terminals, and an external capacity does not influence the breaking down effect.

The experiments I have described on the electric strength of thin layers of glass showed that a number of Franklin plates one tenth of an inch in thickness could be charged in multiple and discharged safely in series. I had constructed at first an apparatus similar to that described by Planté. I speedily found, however, that the design employed by him would not enable me to utilize the full energy of 10,000 cells, for short circuiting would occur in the apparatus. The form described by Planté was therefore replaced by the one shown in Plate I., and in plan and elevation in Plate II. (Figs. 1 and 2).

Figure 1, Plate II., represents an elevation of one end of the apparatus, and Figure 2 a plan of this end. The condensers are shown at C in Figure 1, but are not represented in Figure 2, in order that the connections may be more clearly seen. In Figure 1, H is a handle which moves by means of the link work D both levers L and L' at once. When the lever L is lowered, conductors running along a and a_1 are brought in contact with the coatings E and E' of the plate condensers, C connecting them in multiple. At the same time the lever L' is lifted. When, however, the lever arm L is lifted, L' descends until the diagonal

connector running along b and b' are brought in contact with the coatings E and E' in such a manner as to connect them in series. The conductors connected with the lever arm L extend beyond the connecting arm D, in order to make connection with the terminals of the storage battery B. This extension is necessary in order to prevent any possibility of a return discharge through the battery. T represents one of the terminals of the machine, — which is a special arrangement of the apparatus consisting of spheres one foot in diameter, and thus give a scale of estimation of the size of the apparatus. There are one hundred and fifty plate condensers forty by fifty centimeters.

Lord Kelvin, in a paper dated April 12, 1860,* entitled "Measurement of Electromotive Force required to produce a Spark," states that "there is a much less rapid variation with distance of the electrostatic force preceding a spark at the greater than at the smaller distance. It seems most probable that at still greater distances the electrostatic force will be found to be sensibly constant, as it was certainly expected to be at all distances."

Professor Elihu Thomson, by means of transformers, has obtained sparks of fifty to sixty inches in length, and has estimated the necessary voltage to produce a spark of 80 cm. at 500,000.

This estimate A. Heydweiler † thinks is very much too great, and he believes that 100,000 would be nearer the truth. My investigations show conclusively that the estimate of Professor Thomson is far nearer the truth than that of Heydweiler, and instead of being lessened it should be increased.

In a late paper on the tension at the poles of induction apparatus, A. Oberbeck ‡ states that a potential difference of 60,000 volts under given conditions can produce a spark of more than 10 cm. in length. It is difficult to obtain consistent results by the use of induction coils and transformers.

My results show that Lord Kelvin's conjecture, that the electrostatic force necessary to produce a spark in air remains sensibly constant for all distances beyond the limit he describes, is correct up to the voltage of one million; for when the length of spark is plotted as abscissas, and the corresponding electro-motive force as ordinates, a straight line is obtained. Planté calls attention to the fact that the loss of energy resulting from the transformation of dynamic into static electricity is in

* Papers on Electrostatics and Magnetism. Macmillan, London, 1872, p. 258.

† Wied. Ann., No. 48, p. 231, 1893.

‡ Wied. Ann., No. 9, p. 109, 1897.

the case of his apparatus much less than in induction apparatus. This remark applies with great force to the modern use of transformers for the production of high tension effects. With the improved form of rheostatic machine which I have had constructed, one third of a horse-power will produce the effects which have hitherto required the employment of thirty to forty horse-power.

Up to the point of one million and a half volts the length of the electrical discharge in air appears to be closely proportional to the electromotive force. When this voltage is exceeded, the length of the spark no longer increases in proportion to this force. For instance, an electromotive force of approximately three million produces a spark of about seven feet in length, two hundred and ten centimeters, when it should excite one at least ten feet in length. The reason of this diminution in length is readily seen when the operation of my apparatus is examined in the dark. From both terminals and from the conductors to the terminals there is a luminous brush discharge to the walls and floor of the room. The main discharge between the terminals is so to speak shunted through the air, which breaks down with facility at such high voltages. The high electromotive force exerts a similar action to that of diminished air pressure.

It is thus interesting to compare these conditions further. I therefore connected in multiple two Leyden jars, of about five thousand electrostatic units each, with the poles of five thousand of my cells, and measured the disruptive discharge in a receiver which contained air at ten centimeters pressure. The length of the discharge at this pressure was approximately eight centimeters, when the jars were charged with ten thousand cells. The length of this discharge was fourteen centimeters. Here twice the voltage did not produce twice the spark length. The diminution of length was evidently due to a species of shunting through the air, which had become a relatively good conductor. Indeed, one sees the luminous area of discharge on the positive terminal extend farther and farther in the case of pointed terminals from the point of the terminal.

In ordinary atmospheric air, therefore, the same increase of electrical conductivity takes place under the action of great electromotive force. It is difficult to make exact measurements of the action of such powerful discharges; but the following qualitative experiments, I think, will illustrate my meaning. When discharges produced by one million volts and over are excited between terminals six feet apart in tubes filled with ordinary water, the tubes are speedily burst, and when the phenomenon is carefully examined it is perceived that disruptive sparks occur on

the surface of the water inside the tubes which vaporize the water and thus lead to an explosion. The layer of air conducts more readily than the water. The same phenomenon can be shown by interposing a conductor made of plumbago and infusorial earth of about ten thousand ohms resistance between the terminals of the apparatus. A spark passes over the surface of such a conductor through the air, if the length of such a conductor does not exceed ten or twelve inches. The breaking down resistance of atmospheric air for such high voltages between terminals this distance apart is therefore less than ten thousand ohms. The same phenomenon is observed in the case of paraffine oil, which exhibits between pointed terminals a resistance of only a few thousand ohms for distances of six to eight inches. The actual resistance after breaking down falls to two or three ohms. This I have shown in a previous paper.* To still further study this breaking down of air insulation I carefully measured by Kohlrausch's Bridge method a liquid resistance consisting of diluted sulphate of copper of about one thousand ohms. The terminals in the tube were disks of copper about one square centimeter in area. It was found that the spark preferred to jump through five centimeters of air to passing through the sulphate of copper. The entire range of my experiments precludes to my mind the idea that this effect is due entirely to polarization of the electrodes. The air evidently breaks down with increasing readiness when the electromotive force is increased beyond a certain limit. This is true also of liquid dielectrics like oil. One of the most striking experiments in this connection can be performed by coating a board with a thin layer of plumbago, which is polished upon the surface in such a manner as to make a resistance of about one thousand ohms between broad terminal bands of copper. When a discharge under a difference of potential of one million volts passes between the terminal bands which rest on the coated surface, the entire surface is luminous. If an orange is interposed between terminals of the apparatus which gives over two million volts, it glows in the dark like a golden Chinese lantern, and the discharge passes beneath the rind and over the liquid portion of the conductor. These experiments make it clear to my mind that the disruptive effects of lightning in rending trees and shattering structures is due in large measure to the expansion of confined air or to the sudden formation of steam produced by the electric spark preferring to break down the air to overcoming the resistance of the poor solid conductor.

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* These Proceedings, XXXII. 253.

The effects in air of a voltage of three million are extremely suggestive of the great energy in ordinary flashes of lightning. This voltage will produce sparks six to seven feet in length in ordinary air between small spheres. These discharges closely resemble lightning discharges. They can be obtained of nearly three feet in length from one terminal of the machine, the other terminal being insulated, by bringing near this terminal a conductor which is connected with the ground. It is evident that the electrical circuit is completed through the air to the insulated terminal. When the apparatus for discharging the Leyden jars or Franklin plates was first set up, the coated surfaces of these plates were not more than a foot from the floor. It was speedily discovered, when the room was darkened, that there was a powerful brush discharge to the floor. The entire apparatus was then lifted three feet. In this case there was a gain in the length of discharge which could be obtained; for the air resistance was thus increased. The apparatus is now peculiarly well situated, being three feet above the floor and at a distance from the walls of the room. When, however, the discharge takes place, one feels as if a window had been suddenly lifted, letting in a gust of wind, one's coat lifts, and sparks can be drawn from the neighboring walls. In order to get the full effect of such a voltage in producing discharges, the apparatus should evidently be placed thirty or forty feet above the earth, and should be remote from other masses.

Photographs of these powerful discharges closely resemble those taken of lightning. It is evident to my mind that many of the peculiarities of lightning flashes are due to imperfection in lenses, or to a want of focus. The so called ribbon discharge can be closely imitated by putting the camera out of focus. When a portrait lens of large aperture is employed, many details are obtained which are not shown by the ordinary landscape lens. Thus Plate III., taken by a Dallmeyer portrait lens, represents a single discharge from a sphere one foot in diameter to a long linear conductor which formed the positive terminal. The main discharge was between four and five feet long, and the air between the terminals was filled with a powerful brush discharge, which passed off at right angles to the surfaces. The portrait lens also shows that a single discharge is really made up of to and fro oscillatory discharges; for bifurcations are seen pointing in opposite directions on the line of discharge.

The effect of the high electromotive force which can produce such powerful discharges in air is also of great interest when it is examined in rarefied gases. The spectrum of hydrogen does not appear to be

materially changed from the well known form obtained by interposing a Leyden jar in circuit with an ordinary Ruhmkorf coil. The four most prominent lines are present. Further investigation will be necessary to determine whether more lines are brought out by the increased electromotive force. The spectrum is exceedingly brilliant.

In a previous paper it has been pointed out that the instantaneous development of heat in disruptive discharges through hydrogen when the peculiar spectrum observable in stars is obtained is very great.* This spectrum is seen in the solar prominences, and therefore indicates a very high temperature, apparently much higher than the surface of the sun, which shows the fluted spectrum of carbon which can be produced in the electric furnace. This high temperature might be due to explosions of gas from the body of the sun, or it might be possibly caused by electric discharges through the masses of gas thrown up by some explosive action. The long continuance, however, of this spectrum of hydrogen indicates a prolongation of the state of high temperature. Electrical discharges occurring oftener than sixteen times a second might produce the spectrum and still account for the apparent high continuous state of temperature of the gas.

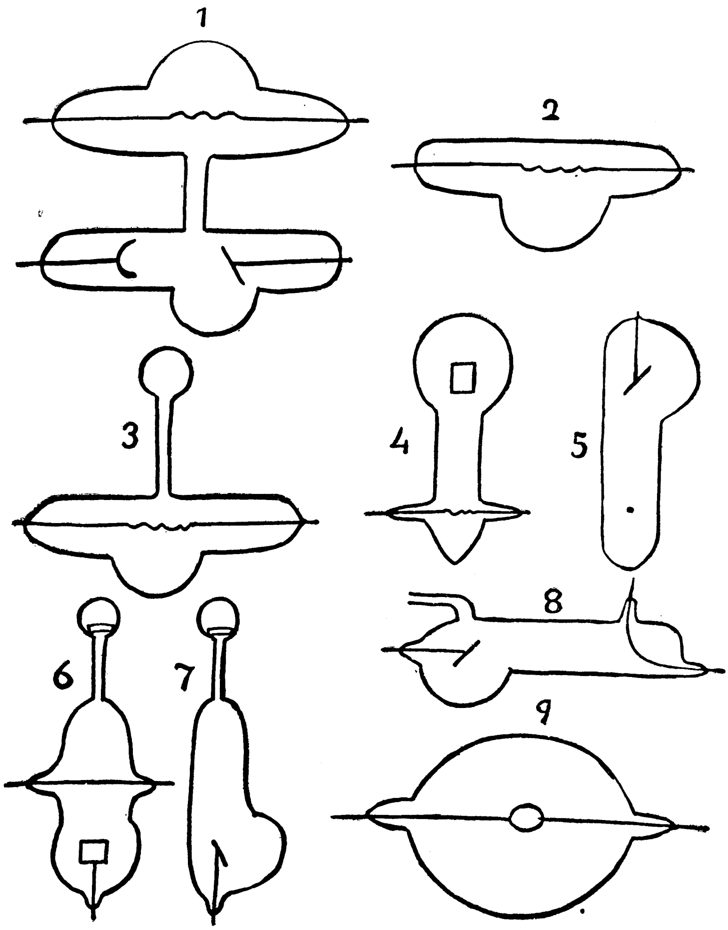
Leaving, however, for the present a more careful study of the hydrogen spectrum under the conditions of extremely high electromotive force, I pass on to the effects produced by such voltage in very highly rarefied media such as are contained in Crookes tubes. In these experiments I have been greatly assisted by Mr. John E. Burbank, graduate student.

The experiments were conducted with Crookes tubes containing no interval between the anode and the cathode; and no discharge therefore, in the usual sense, occurred in the tubes. A continuous conductor was led through the rarefied tube, and it was discovered that the X-rays were given off from every element of this conductor at right angles to its surface when a disruptive discharge occurred in the circuit of which the tube formed a part. This remarkable result was obtained by means of the very high electromotive force obtained by the apparatus represented in Plate I., which was charged by ten thousand storage cells.

The first tube is shown in Figure 1. It consisted of a straight wire tube joined to an ordinary Crookes tube of the focus pattern. This latter tube was joined to the straight wire tube in order to test the vacuum in the latter, and to be sure that the necessary conditions existed for the production of the X-rays. When the terminals of the straight wire tube

* Am. Journal of Science, Vol. III., April, 1897.

were connected to the Planté machine, and the latter was excited, the entire tube fluoresced brilliantly. This fluorescence was especially bright in the connecting tube between the straight wire tube and the Crookes tube, and a beam of light passed across the Crookes tube and formed a fluorescent spot on its bulb.



FIGURES 1 TO 9.

Photographic plates were exposed opposite to the thin bulb on the straight wire tube. These plates were carefully insulated from the ground, and were covered in one case with a sheet of hard rubber an eighth of an

inch in thickness, and in another case by a sheet of glass about half an inch in thickness. A powerful brush discharge was seen in the dark room to pass from the thin bulb of the tube to the insulator which covered the plates, and on developing the plates they were found to be covered with star-like clusters surrounded by nebulous patches. It was evident that the brush discharge had produced discharges at the surface of the dry plate, even through plates of glass half an inch in thickness. Moreover there was a general darkening of the surface of the plate which indicated the action of the X-rays. No metallic objects could be placed upon the dry plates, for a powerful spark immediately passed to them and punctured the tubes. The darkening, however, was apparently diminished under strips of glass, although the effect of the brush discharge masked the effect of the X-rays.

Before the straight tube was exhausted powerful brush discharges were given off at the ends of the tube. When the tube was exhausted these brushes were much diminished and were replaced by a powerful brush, which came off from the straight wire through the bulb of the tube and speedily punctured the latter when any object, even an insulator, was brought within six inches of the bulb. The most interesting result obtained with this form of tube was the production of the so called X-ray burn by means of the brush discharge from its bulb. When the back of the hand was exposed to this brush discharge, which assumed a peculiar forked nature in the dark room, a peculiar prickling sensation was experienced, and all the symptoms of the well known X-ray burn developed. The skin when examined under a microscope exhibited an appearance similar to that shown by the photographic plate. There were centres of inflammation surrounded by regions of lesser degrees of burn. It seems evident that the so called X-ray burn is due to an electrification, — a discharge at the surface of the skin, — and this electrification may or may not be accompanied by the X-rays. The first form of tube was then abandoned, and a straight wire tube alone (Fig. 2) was employed. Similar results were obtained with this tube. It was significant that the whole interior of this tube fluoresced brilliantly when it formed part of a circuit through which a disruptive discharge passed. This latter form of tube was replaced by that represented in Figure 3. A side ending in a thin bulb was added to the straight wire tube. The same phenomenon was exhibited by this tube: in addition, a brilliant fluorescence filled the side tube, which appeared to flow in or flow out of the narrow tube which ended in the small bulb. One is reminded by this phenomenon of Poynting's hypothesis of the flow of energy into a wire. This form of

tube was replaced by a straight wire tube which is represented in Figure 4 and Figure 5 (side view). A straight wire passed completely through the tube, and was in circuit with a line on which there was a rapid change of potential. At one end of this tube opposite a thin bulb blown on the tube is a piece of platinum foil inclined like the ordinary focus plane in a focus tube. At first we connected this focus plane with the ground, and, having ascertained that X-rays were given off very strongly from this foil, we removed the ground connection and substituted for it a sheet of zinc. The tube still gave off X-rays. We then removed the sheet of zinc, and found that X-rays were given off with undiminished strength. This tube was then modified into the form represented in Figure 6 and Figure 7 (side view). The straight wire occupied the middle of a tube: in one end of this tube was placed a focus plane of platinum, and at the other end there was a long narrow tube which ended in a thin bulb. In this bulb was a crystal of calcite which was confined in the bulb by the narrowness of the bore of the connecting tube. This tube showed that X-rays were given off at right angles to the straight wire, for the calcite fluoresced a brilliant red and the fluoroscope showed X-rays proceeding from the inclined piece of platinum. This form of tube, moreover, showed that the X-rays are reflected, so to speak, from the interior surface of the glass, for there were multiple shadows of the wire on the sides of the tube which were produced by the X-rays of varying intensity that were developed on the surface of the glass, and which in turn, proceeding from this surface at different angles, produced elongated shadows. In the next form of tube, the wire passing through the tube was no longer straight, but was bent in the manner represented in Figure 8. In this form of tube there was a brilliant caustic formed on the sides of the tube opposite the concave side of the wire, and this brilliant caustic threw distorted shadows of the bent wire on the opposite side of the tube. It was evident that the X-rays were given off at right angles to the surface of this wire, and therefore coincided in direction with the lines of electrostatic force. We next experimented with the form of tube represented in Figure 9. This consisted of a large thin bulb five inches in diameter, enclosing a continuous conductor, the centre of which consisted of an aluminium mirror. When this tube was exhausted to a very high degree, the mirror formed a bright fluorescent spot on the bulb, the position of which could be readily changed by means of a magnet. When the exhaustion was carried to a very high degree, reversing the current from a Ruhmkorf coil through the tube caused no marked difference in the appearances in the tube; at a lower degree, however, a marked difference resulted.

With the employment of a powerful Ruhmkorf coil giving sparks of at least eight inches, X-rays could be detected in this tube, and when the tube was connected with the Planté machine, the X-rays gave strong effects in the fluoroscope.

In order to test the question whether the so called cathode rays and X-rays are generated primarily only at the cathode, a very large resistance of distilled water was interposed in the circuit with the continuous wire tube (Fig. 9) in order to damp any oscillations which might arise. The circuit thus consisted of the tube, the water resistance, a spark gap, and the secondary coil of a large Ruhmkorf. The tube was connected at first permanently to the air pump. As the exhaustion proceeded a beam of rays proceeded from the mirror on the continuous conductor which was focused on the wall of the tube. This beam was more brilliant and produced a stronger fluorescence on the tube when the wire was negative than when it was positive. At a higher stage of the vacuum, however, very little if any difference could be detected in the appearance of the tube, and X-rays could be detected outside the tube opposite the fluorescent spot caused by the mirror. That is, the X-rays were given off when the wire constituted both the cathode of the circuit and also the anode. It seems, therefore, that the term cathode rays is not a general one. It would seem that electric rays might be a more comprehensive one for both cathode rays and X-rays.

Furthermore the phenomenon of electrostatic induction plays an important part in the phenomena of the so called X-rays. When the tube represented in Figure 9 had reached a certain stage of exhaustion, a bit of tin-foil connected to a zinc plate 10 by 16 cm. and 1 cm. thick, was stuck upon the outside of the tube where the mirror formed the fluorescent spot. This zinc plate was carefully insulated from the ground. It was seen that a bundle of rays was reflected by the tin-foil to the opposite wall of the tube, showing a well defined shadow of the mirror and the continuous conductor on this wall. The direction of this shadow could be changed at will by changing the position of the tin-foil. This phenomenon was produced both when the wire was the cathode and when it was the anode. It can be explained on the hypothesis that a layer of electrified particles is held by a condenser action on the wall of the tube, and that the fresh coming particles are strongly repelled by those that have accumulated at the spot.

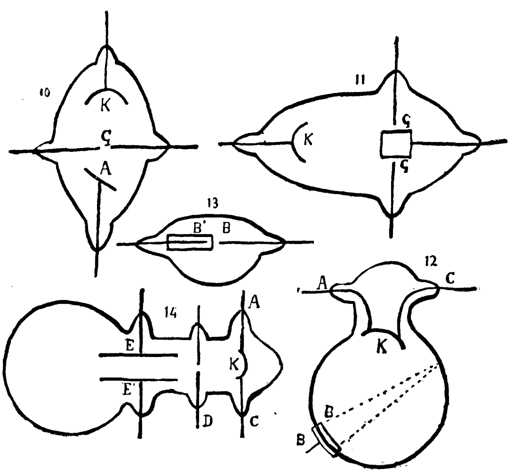
The behavior of aluminium toward the X-rays is so remarkable that it merits especial investigation. Can it be that it manifests a remarkable condenser action toward the high electromotive forces which produce

the X-rays, similar to the action which has been observed at lower voltages? * We connected to the air pump, at the same time, two exactly similar tubes, one of which had two pointed terminals of platinum, the other two pointed terminals also; but one consisted of aluminium and the other of platinum. The discharge from a Ruhmkorf coil was sent through these tubes, which were in multiple circuit. At a certain stage of the exhaustion it was seen that the discharge passed more easily when the aluminium wire was made a cathode than when it constituted the anode. When the wire terminals in both tubes were made of thin disks, the difference was less marked. This might have been surmised, from previous investigations on the effect of form of electrodes on resulting polarization.† It may be that the anomalous action of aluminium in respect to X-rays is due to a species of dielectric polarization on the surface of the platinum, and that thus the surface becomes a new source of electrostatic stress, similar to that which was observed by connecting a bit of tin-foil and a capacity with the tube. Since we are dealing with very high differences of potential and with high charges on the ions, the instantaneous exhibition of electrical energy is very great, and might probably explain the diffusion of this energy through the air. According to this hypothesis the light manifestations of the X-rays arise only at the fluorescent screens, or at other suitable surfaces.

In continuing these studies of the electrical discharge in a vacuum, one is naturally led to examine the breaking down of the resistance of rarefied spaces by means of the X-rays which has been noticed by many physicists. The form of tube employed in the first experiment is shown in Figure 10, in which K is the cathode, A the anti-cathode, and C the gap between two terminals connected through a galvanometer with a battery. At the X-ray vacuum the smallest voltage which could set up a current when the gap C was illuminated by the X-rays was 240 volts. In the next form of tube which was employed (Fig. 11), the gap C was replaced by the gaps GG' placed on opposite sides of the anti-cathode and very near it. The breaking down effect was strong in this form of tube; and the residual effect of the X-rays was very marked after they had ceased to be excited. For instance, if the battery current would just pass when the X-rays were illuminating the tube, it would also flow some seconds after the cessation of the X-rays, showing the residual effect of these rays. In order to form an estimate of the resistance offered to disrup-

* L. Graetz, Wied. Ann., No. 10, 1897, p. 323.
† Karl Robert Klein, Wied. Ann., No. 10, 1897, p. 259.

tive discharges by the X-ray vacuum, the resistance of the X-ray tube was measured in the process of pumping when it had reached a pressure of 2 mm., at which stage the rarefied air appears to have the greatest conductibility, and it was next measured at the X-ray vacuum, the gap *C* being illuminated by the X-rays. These measures of resistance were made by using an additional air gap in the circuit, and by the method of dampening of oscillations. Nine oscillations could be obtained through the rarefied air at 2 mm. pressure, while under the same conditions eleven oscillations were obtained in the X-ray vacuum. This shows that, when this high vacuum is broken down, it exhibits less resistance than air at 2 mm. pressure.



FIGURES 10 TO 14.

In another experiment the gap *C* was placed in a tube which was separate from that in which the X-rays were produced, in order to prevent any disturbing effect of the current which produced the X-rays. The same breaking down effects were observed, although they were lessened by the necessary weakening of the X-rays, since they had to pass through two surfaces of glass separated by a layer of air.

In order to confirm the statement that this breaking down effect is exerted at the cathode in the tube through which a battery current is led, one of the terminals was covered with a piece of thick barometer tubing which projected beyond the metal of the terminal *B'* (Fig. 13). This thick glass served to diminish the effect of the X-rays on this

terminal. By reversing the terminals it was then found that the breaking down effect was exerted principally upon the negative terminal.

Since these investigations had shown that there are anode rays as well as cathode rays, it was of interest to investigate the breaking down effect of the anode rays. The form of tube was similar to those before described, being provided with a continuous conductor, which could be made positive or negative at will; and it was found that the breaking down effect was manifested also by the anode rays.

With the tube represented in Figure 11, it was discovered that a difference of potential of 10,000 volts between GG' could produce the X-rays, and indications of them could be obtained at 2,500 volts; and it may be that they exist even in discharges produced at a less voltage; and is it not possible that they may be the initial cause of the breaking down of even atmospheric air, by setting up lines of polarization or stress?

The conviction has been expressed that electrostatic induction plays an important part in the production of the X-rays, and the following additional experiments were undertaken with a modified form of tube. The first experimental tube was constructed as follows. A continuous conductor $A\ K\ C$ (Fig. 12) was enclosed in a Crookes tube. One portion of this conductor consisted of an aluminium mirror, K. The wires leading to K were covered with glass tubing, and the metallic surface of the back of K was coated with an insulating glaze. The X-rays produced when K was made the anode or cathode could be diverted in any direction by means of a piece of tin-foil placed on the outside of the bulb and connected with a suitable capacity, which was carefully insulated. A metallic concave disk was then enclosed in the bulb. This disk, being entirely disconnected from the continuous conductor $A\ K\ C$, could be moved into any position by suitably inclining the tube. The disk B' served to generate by induction a new beam of rays, which was much intensified by placing a disk of tin-foil on the outside of the glass opposite the disk inside the bulb and connecting this tin-foil with an insulated piece of metal.

The material of the enclosed disk did not appear to influence the result. In one case it was made of lead, and in another of aluminium. It was not necessary that the inner disk should be at the focus of K. A number of such disks could doubtless be employed, all of which would manifest such inductive action.

In order to see if we could detect any refraction of the lines of electrostatic force, a disk of paraffine having the same radius of curvature as the outside of the glass bulb was placed at a certain position on the bulb,

and a piece of tin-foil was then placed on the outer surface of this disk B of paraffine and connected with a suitable insulated capacity. In this case the fluorescent spot produced by electrostatic action was spread out and ill defined, much as if a disk of glass of similar form should be placed in the path of rays of light coming from a concave mirror.

It therefore seems to us that in the generation of the X-rays the electrostatic lines of induction are suddenly formed together with currents of displacement, and that the wave front quickly advances, probably with the velocity of light, and that the molecular effects observed are merely the concomitants of the electromagnetic disturbances.

Since the production of the anode rays requires a higher vacuum than that at which the cathode rays are excited, we were interested to ascertain if the molecules of the gas under their influence possessed a greater or less velocity than that already found for particles moving from the cathode. We accordingly constructed a tube which was substantially similar to that employed by Prof. J. J. Thomson in his investigation of the effect of the electrostatic field on the path of the molecules excited by the cathode ray.* The modifications consisted in the substitution of a continuous conductor $A\ K\ C$, Figure 14, for the cathode and anode of his tube. In the figure, E and E' represent plates maintained at a known potential, thus giving an electrostatic field, and D is a suitable diaphragm. We expected to obtain a greater or less deviation of the position of the fluorescent spot formed on the surface of the bulb by the anode rays emanating from K. The inductive effect, however, of the plates E and E' was so great when K was positive that no measures were possible. This form of tube thus exhibited still more strongly the effects of electrostatic induction, and confirmed us in the belief that electrostatic induction is an important phenomenon in the generation of the X-rays.

Conclusions.

1. Beyond one million volts the initial resistance of atmospheric air to electrical discharges becomes less and less, and in certain conditions can be as low as one thousand ohms between terminals two or three inches apart. The curve therefore representing the relation between length of spark and electromotive force departs from a straight line beyond one million volts and approaches the axis which represents the increase of voltage.

2. When the initial resistance of highly rarefied air is broken down by means of the X-rays, it exhibits less resistance than it does at the

* Phil. Mag., October, 1897.

point of 2 mm. pressure, when it is generally considered of the greatest conductibility.

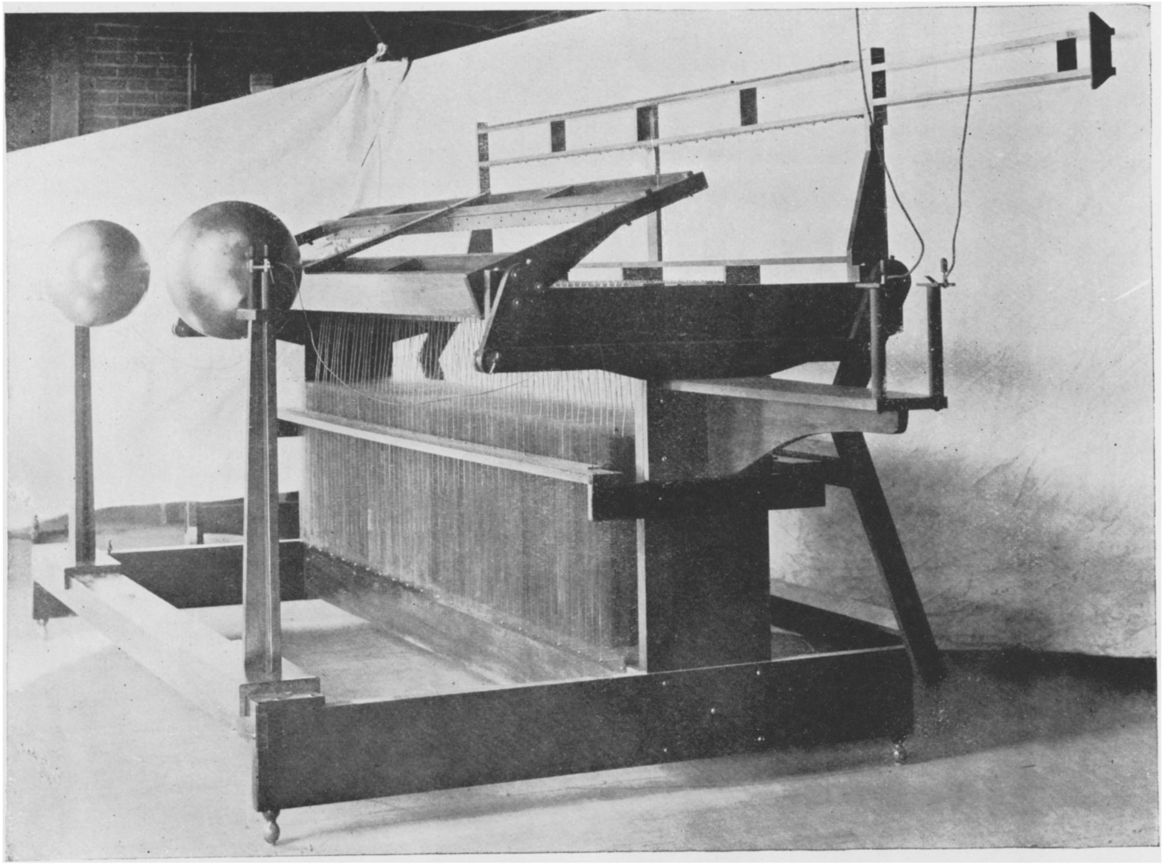
3. There are anode X-rays as well as cathode X-rays, and these rays exhibit all the peculiarities of the cathode rays; such as the excitation of fluorescence, phosphorescence, and the peculiar action of breaking down the initial resistance of air and other gases.

4. The X-rays can be distinctly produced with an electromotive force of 10,000 volts, and there are indications of them at a voltage of 5,000.

5. Electrostatic induction is an important phenomenon in that of X-rays. Experiments indicate that the X-rays are evidence of an electromagnetic disturbance, to which lines of electrostatic form are set up in the medium, and that the disturbance therefore travels with the velocity of light, and is accompanied by molecular excitation, which however is only one of the concomitants of the electromagnetic disturbance.

6. The mechanism, therefore, of the production of the X-rays appears to be a setting up of electrostatic lines of induction along which the electromotive force or difference of potential acts, and a production of an electromagnetic wave or impulse. The stress in the medium reduces its initial resistance, and the X-rays' radiation becomes less and less energetic after a certain interval the longer the Crookes tube is excited; for the increased conductibility of the medium persists after each pulse of such radiation, and therefore the difference of potential between the terminals speedily drops, or does not rise to the full value which the induction machine is capable of developing.

7. The behavior of highly rarefied media to powerful electric stress is analogous to that of elastic solids to mechanical stresses. A so called vacuum which acts like an insulator when submitted to an electromotive force capable of producing a spark of eight inches in air (approximately two hundred thousand volts) breaks down under the stress of three million volts. A single discharge with this voltage through highly rarefied media produces the X-rays in such a powerful manner that a photograph of the bones of the hand can be taken in one millionth of a second. During the discharge the apparent resistance of the rarefied medium is only a few ohms. In this case the medium seems completely to lose its elasticity so to speak, and is ruptured. The elastic solid analogy seems to explain the behavior of highly rarefied media toward powerful electric stresses. The generation of the X-rays is accompanied by a powerful electrostatic stress which breaks down the so called elasticity of the medium. The question of the electrical conductivity of the ether, it seems to me, can be studied best from the elastic solid point of view.



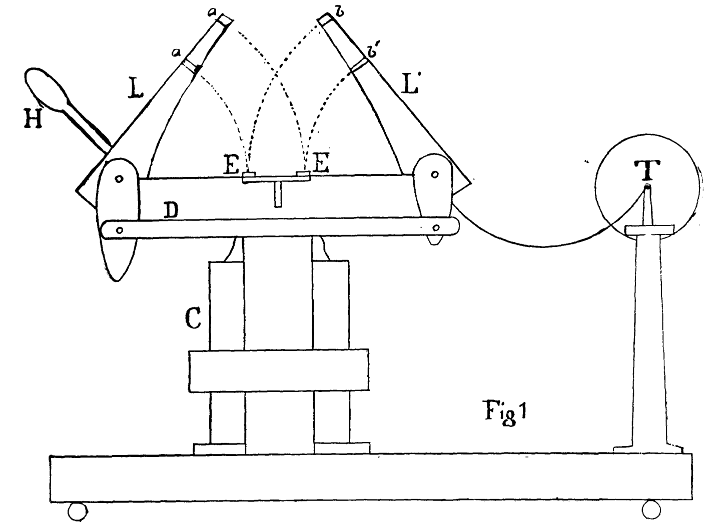


Fig 1

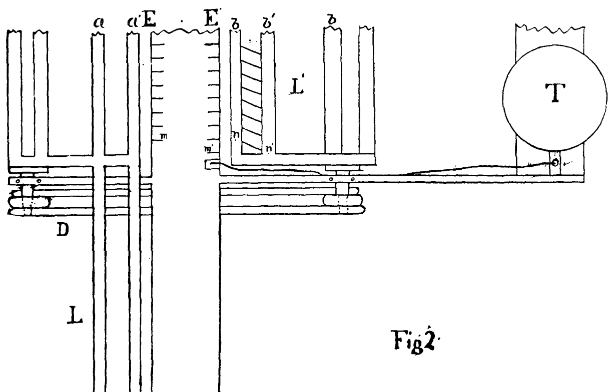


Fig 2